

## GLOBAL WEATHER AWARENESS

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1 May 1996

19970127 093

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 11 May 1996		3. REPORT TYPE AND DATES COVERED Scientific
4. TITLE AND SUBTITLE Global Weather Awareness			5. FUNDING NUMBERS PE 62601F PR 6670 TA GR WU 15	
6. AUTHOR(S) Robert A. McClatchey Darryl P. Greenwood*				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Phillips Laboratory/GPA 29 Randolph Rd Hanscom AFB, MA 01731-3010			8. PERFORMING ORGANIZATION REPORT NUMBER  PL-TR-96-2089 ERP, No. 1189	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES *Chief Scientist, Air Force Rome Laboratory, Rome, NY 13441-4514				
12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The requirements of the military for meteorological information greatly exceed those of the civilian world because of the timeliness, specificity, and responsiveness required. New sensor and sensing techniques require development to meet these needs, especially as related to an imperative for global weather awareness, often in adverse conditions. Military forces must be prepared to deal with conditions that are access-denied and hostile, as well as regions that have no indigenous capability. Naturally this would indicate expanded sensing from space, but this is perhaps unaffordable at the present time. Thus a concept based on an Uninhabited Air Vehicle designed to survey conditions in the theater is worthy of consideration, because of advances in sensors, electronics, communications, and packaging.				
14. SUBJECT TERMS Remote sensing Weather sensing Meteorological sensing			15. NUMBER OF PAGES 16	
Weather intelligence Space-based observations High resolution sensors			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified		18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified		19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified
			20. LIMITATION OF ABSTRACT SAR	

## Preface

In the spring and summer of 1995, the second author spent considerable time deliberating with the Sensors panel of the Air Force Science Advisory Board New World Vistas Study, which culminated in a voluminous report to the Secretary of the Air Force (scheduled for publication in December 1995). Like all such plenary studies, there was an attempt to be both thorough and useful — goals that tend to pull in two directions. One area that was thought to deserve particular attention was global weather awareness, because of unique military requirements as well as some challenging technical objectives. The writeup that follows was prepared for the report, but owing to many other such writeups it was not possible to include it in its entirety. Thus we provide it in full for those who feel that these thoughts can be of some value to them in their planning processes.

Contributions, in text and in thought, are gratefully acknowledged from Capt. Wood (88th WF/OSWA, Wright Patterson AFB OH); Dr. William Smith (U. of Wisconsin); Mr. Stan Schneider and Col. John Goyette (of the NPOESS Integrated Program Office); Dr. Wayman E. Baker (NOAA/National Weather Service); Drs. Joe W. Waters, Mustafa Chahine and Fuk Li (JPL); and Drs. Ken Fischer and Jack Walker (ERIM).

# Global Weather Awareness

## 1. INTRODUCTION

Knowledge of weather conditions is extremely important to Air Force missions, with requirements that go well beyond those in the civilian world. US civilian weather forecasting emphasizes prediction of atmospheric conditions, including severe storm warning, because weather influences commerce, transportation, entertainment, and general comfort. NOAA and the National Weather Service, representing the civilian side of the US government, concentrate on the North American continent and environs, and look beyond only to the extent that additional data are needed as input to the circulation models. The meteorological needs of the military include but go well beyond the civilian scope because of an inherent requirement to operate globally – anywhere and anytime – and over very specific sites, often in poor visibility conditions.

To complicate matters, areas of interest to the military are often access-denied, thus emphasizing remote sensing (satellite-, aircraft-, and ground-based). The Air Force, by the very nature of its mission, needs to know weather information in areas where such information is the most difficult to obtain. To generate the Air Tasking Order, the planner needs to know site-specific conditions with forecast lead times of 6-12 hours. Aircraft and munitions types are changed based on the expected weather, with some missions being put off to wait for better conditions, and others taking advantage of clouds and poor visibility. Performance of precision strike weapons is especially sensitive to atmospheric conditions of clouds, dust, smoke, and other aerosols. Whether aerosols are wet or dry is important to infrared sensors and seekers. This information is not routinely available for many areas of the world, and based on the experience of Desert Storm, was critical to the application of air power.

Despite the added difficulties, the need for global three-dimensional observations is common to both the military and civilian worlds of meteorology; thus the Defense and Commerce Departments have started collaborating to converge the Air Force's DMSP (Defense Meteorological Satellite Program) and NOAA's Polar Satellites into one satellite system for the future. The NPOESS (National Polar-Orbiting Operational Environmental Satellite System) Interim Operational Requirements Document (IORD) is an excellent starting point for detailed information on military (as well as civilian) meteorological observations for the next 10-15 years. The first NPOESS satellite is slated for launch in 2008, but many technologies needed to meet the baseline requirements are not yet here. A particular example is active sensing technology, using lasers to provide better information on winds and aerosols, and microwave sources to provide better information on dense aerosols, including clouds.

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Received for publication 1 May 1996

## 2. MEASUREMENT NEEDS

Accurate short-term prediction of weather over a given site requires information on the synoptic evolution of weather patterns in the area over the previous 2-3 days as well as very precise knowledge of the current atmospheric state in the vicinity of the site of interest ("now-casting"). The accuracy of short-term predictions is determined by the quality of the weather prediction models being used and the accuracy of the information being input to these models. The accuracy of all these short and medium forecast models is limited by the spatial and temporal spacing of measurement points, with inputs from satellites, aircraft, and ground-launched radiosondes. With increasing advances in computational power, forecast models have become limited primarily by the adequacy of data, and this is especially the case for non-US sites. Outside of the United States, non-satellite observations range from good to non-existent, with the majority of the earth's surface falling in the latter category.

Virtually all weather forecasting today is done using a variety of gridded atmospheric dynamics models that require frequent inputs of atmospheric parameter profiles. A wide variety of parameters affect local weather, such as vegetation cover (albedo and surface drag), bodies of water (source of moisture and heat source or sink), and topography (local wind flow dynamics), but most of these change on much slower time scales than the weather. The key time-dependent parameters of interest for weather forecasting are: (1) temperature (2) dew point (3) pressure (4) wind speed and (5) wind direction. In the future, forecast models may yield significant improvements based on global cloud input. Still, a capability for high quality, three-dimensional data is required.

The fundamental limitation in accuracy of forecast models currently is the temporal and spatial sampling of these parameters. The National Weather Service utilizes as a principal means of data collection a series of rawinsonde launches every 12 h at sites spaced roughly 200 nmi apart throughout the CONUS and Hawaii. Rawinsonde launches elsewhere in the world are more or less available. Over ocean or at high latitudes, sampling is frequently very limited, and over access-denied regions there are virtually no rawinsonde data. Satellite sensors likewise suffer from limited resolution and availability. US-developed geostationary-orbit satellites such as GOES view principally United States territory, with sensors that do not penetrate dense clouds. Satellite-based sensors have additional limitations, and deserve considerable attention as this is an area where technology advances can result in substantial improvements in broad-area forecasting. However, satellites are expensive, and geostationary satellites are particularly so. Implementing geostationary satellites to view the whole world may not be cost-effective. Rather, airborne sensors (such as might be carried by Uninhabited Air Vehicles (UAVs) offer potentially cost-effective alternatives. Airborne and space-based sensors will be the focus of the remaining discussion as these are more likely to provide requisite data in access-denied regions.

### **3. SENSOR TYPES FOR GLOBAL WEATHER OBSERVATION**

The history of global weather observations has emphasized satellite-based sensors operating in the visible, infrared, and microwave portions of the electromagnetic spectrum. With a few exceptions, these observing systems have been passive, with sensors falling into two categories: imagers and sounders. Imagers are generally lower in spectral resolution, but higher in spatial resolution than sounders, which provide vertical profiles of quantities of meteorological interest. Furthermore, imagers provide contiguous coverage of the portions of the globe where observations are made. In the future the distinction between sounders and imagers may disappear as technology advances and provides almost instantaneous true four-dimensional resolution (three dimensions in space plus wavelength or frequency).

Initially, imagers operated at visible wavelengths. As technology developed, systems were designed to operate in the infrared and microwave region and provide information on an increasing set of atmospheric parameters. Passive sounders have emphasized measurements of the vertical profiles of temperature and moisture with some success. The military requirements for vertical measurement resolution are clearly not met by current measurement systems. It is here that lidar holds the promise of satisfying future needs.

There is a sort of "Catch-22" in atmospheric remote sensing - in order to "see" the atmosphere, from a satellite or aircraft platform, one must look in a spectral region where the atmosphere emits (and therefore absorbs) radiation or where the atmosphere scatters radiation. In the limit, optically dense atmospheric conditions deny our sensor the possibility of seeing beyond some depth. In general, clouds limit the use of visible and infrared systems for atmospheric remote sensing to cloud-tops or to regions devoid of clouds. In the microwave region, clouds become more transparent, but may still be the major source of error in data interpretation. In principle, this problem may be soluble by space-based radar operating at appropriate wavelengths.

The following sections provide some thoughts and comments on the four sensor technologies mentioned above as they might be improved or implemented to provide a more complete picture of the global atmosphere: 1) Passive infrared; 2) Passive microwave; 3) Active visible/infrared (lidar); 4) Active microwave/mm-wave (radar).

#### **3.1. Passive Infrared**

Passive infrared sensors operating today need more channels, more resolution and a higher refresh rate. The passive infrared includes the near infrared from 0.8 to 3.7  $\mu\text{m}$ , in which satellite sensors receive most energy from reflected sunlight, as well as the thermal infrared from 3.7 to 100  $\mu\text{m}$  where most energy is from thermal emission from the surface, clouds, or the atmosphere.



In general, each atmospheric window should have one or more channels to better address clouds and surface properties such as temperature, snow cover, sea ice, and vegetation. Windows at 1.6, 2.1, and 4.6  $\mu\text{m}$  are not routinely utilized but should be in future systems. Moreover, the windows from 3.5 to 4, and 8 to 12  $\mu\text{m}$  are sensed now, but significant information would be available if a total of six channels were sensed in these windows. Water vapor absorption bands near 1.1  $\mu\text{m}$  and carbon dioxide bands near 4.3 and 15  $\mu\text{m}$  provide information on water vapor and atmospheric temperature. The refresh rate badly needs the improvement that geostationary platforms can provide. Interferometric techniques, such as planned for future GOES and NPOESS missions, employ not just a few channels, but expand on the concept by generating literally thousands of channels, each at a discretely different frequency.

Because infrared sensing can be done in a variety of bands at relatively short wavelengths, higher spatial resolution is attainable relative to microwave sensing. Unfortunately infrared does not penetrate clouds, and thus does not provide data in a region of interest to the Air Force planner and pilot. More generally though, infrared sensing provides more accurate and higher resolution atmospheric data for the forecasters than do other techniques. To take advantage of the inherent higher resolution, one needs infrared focal planes with large numbers of sensing elements, and cryogenic coolers amenable to long-term, high-reliability operation in space. In both these areas there have been significant advances of late, in part driven by the commercial sector, but one should not overlook the very substantial investment by the DoD in large array HgCdTe, InSb, and PtSi detectors, as well as cryo coolers. Coupled with interferometric techniques, these advanced focal planes offer the potential for exceptionally high spatial and spectral resolution.

With improved resolution comes large quantities of data, which must be processed intelligently and transmitted. At higher data transmission rates, communications channels are increasingly overburdened. This is true not only for passive infrared sensors, but also for all types of sensors – active and passive. Data compression based on not retransmitting images of huge areas where conditions are unchanged is certainly called for, and is being pursued quite vigorously in the commercial field for video phones and the like. To reduce the bandwidth requirements further, there needs to be on-board processing based on techniques unique to the meteorological community. This would indicate the need for vigorous development of application-specific processing algorithms, which would in turn be implemented in commercial hardware.

### **3.2. Passive Microwave**

For present purposes the term “microwaves” is intended to extend through millimeter and sub-millimeter waves, from about 1 GHz to about 1 THz. Current microwave technology is focused on atmospheric window spectral regions at frequencies below 90 GHz for observing surface characteristics and clouds, and at frequencies in the 60-GHz oxygen line and in the 183-GHz water line for remote sensing of temperature and water vapor respectively. The excellent propagation characteristics in the noted microwave window permit penetration of fairly dense clouds, thus permitting mapping of cloud tops and bottoms, as well as densities of multiple cloud layers.



The application of these techniques in the remote sensing of surface characteristics has two shortcomings: 1) Horizontal resolution is limited; and 2) Atmospheric liquid water content (cloud and precipitation) complicates the data interpretation. A way around these problems appears to be the development of Synthetic Aperture Radiometry for space or UAV application. Such systems would have to operate at lower frequencies than current systems (perhaps 5-10 GHz). A key technology issue is the development of large antennas capable of being employed in space. [The issues involving space-based radar are discussed elsewhere in this report.] Alternatively, such systems could be used on high flying aircraft (where smaller antennas will suffice) and provide target acquisition and mapping through clouds and obscurants with high horizontal resolution (down to 1 meter).

The application of passive microwave radiometry to the profiling of atmospheric constituents is currently of limited value for atmospheric sensing due to the poor vertical resolution of measurement. Furthermore, current techniques are inadequate to measure water vapor at high altitudes (above about 9 km). The vertical resolution problem may require revolutionary techniques (an example is the recently proposed radio-occultation technique using GPS satellite signals) and may also require the development of more sophisticated physical/mathematical algorithms to more effectively interpret existing measurements. The measurement of water vapor at higher altitudes may be attainable through the development of new sensors capable of measuring atmospheric emission in the 550-GHz region. Improvement in the horizontal resolution of temperature profiling should improve markedly by developing a sensor operating in the 118-GHz oxygen line instead of the 60-GHz line where sensors currently operate.

### **3.3. Lidar**

Several advanced atmospheric lidar sensors can be developed. These remote sensing devices employ laser transmitters and detect light backscattered from atmospheric aerosols. Aside from the usual backscatter modes — Rayleigh (molecular), Mie (aerosol), and Raman — measurement capabilities can include coherent and non-coherent approaches, fluorescence effects, depolarization, and differential absorption. Such systems hold the promise of measuring profiles of temperature, moisture, thin clouds, aerosols and minor atmospheric species with the very high vertical resolution needed to satisfy many of the currently stated AF requirements. Lidar sensors will be characterized as compact, convertible, rugged, solid state devices capable of airborne and space use. Eye safety considerations are extremely important in the development of these sensors. Generally this implies operation at wavelengths longer than 1.5  $\mu\text{m}$ . Even these devices will be compromised in the presence of thick cloud systems where microwave-radar techniques will have to be employed.

Lidar systems offer perhaps the greatest promise for remote measurement of atmospheric winds, temperature, pressure and water vapor. Of these, wind speed and direction is the greatest need and one with the greatest technical challenges. To date the only means of remotely measuring winds is to observe cloud drift or the effect of winds on ocean waves. In "friendly" territory, such as over the US, winds are measured routinely by aircraft pilots and by the use of ground-based Doppler radars. In data-denied and remote regions, this is simply not possible. Techniques capable of measuring winds from either Mie or Rayleigh scattering would have advantages in that they would not be limited to a specific part of the atmosphere. The technology exists today to measure winds in the troposphere from space with Doppler lidar, but studies have shown the cost is prohibitive, and that there will still be serious data gaps. More modest technology (meant to imply lower laser power and a smaller telescope) can be used to measure winds in the boundary layer, and in the tropics where there is generally higher scattering. This may have the greatest impact on circulation modeling and weather prediction. Serious consideration needs to be given to including Doppler lidars aboard satellites as well as aboard UAVs. Ongoing development of efficient, eyesafe, 2- $\mu\text{m}$  solid-state lasers will permit compact wind-measuring lidars to be built.

Lidars also have particular advantages in sounding for clouds (cloud tops and for low-densities, cloud bottoms). Despite expectations to the contrary, lidars can penetrate some clouds, as demonstrated in the recent Lidar In-Space Technology Experiment (LITE) mission conducted by NASA Langley. LITE was a shuttle-borne sensor that propagated Nd-YAG laser beams at three wavelengths downward to sense incoherent backscatter. Data demonstrated propagation through low-density clouds, sufficient to detect both cloud tops and bottoms to 2-3 layers. Many clouds were too dense to penetrate, and microwave techniques need to be pursued to better map cloud formations.

As electro-optical systems become more sophisticated, they inevitably reach the point where performance is limited by atmospheric optical turbulence. Lidars are being considered for development as atmospheric turbulence sensors, in conjunction with the parallel development of compact, rugged, eyesafe laser technology. Parameters of interest are velocity turbulence and optical (or temperature) turbulence. An airborne lidar capability for remote sensing of velocity turbulence would be of clear utility to aircraft safety. Lidar velocity turbulence measurements, coupled with temperature measurements, would provide a unique capability to profile and image the turbulence eddy diffusion coefficient and would be of value to chemical/biological agent monitoring and modeling, as well as to studies of atmospheric transport and dynamics. Such a lidar would find applications not only in laser system development and adaptive optics research, but also in airborne laser applications, potentially as a real-time decision aid.

Invariably, the main limitations to implementing the necessary lidar technology are the size and lifetime of the laser. Here the meteorological needs will likely follow commercial developments. As solid-state lasers develop, initial systems need to be flown to demonstrate the potential of space-based lidars. The LITE sensor was an excellent example of this.

### 3.4. Radar

Future developments in the technology of active radar systems for meteorological applications of the Air Force are likely to be driven primarily by needs for increasingly detailed measurement and forecasting of clouds. Clouds strongly affect both the surface energy budget and atmospheric heating, both of which are important for forecasting. Surface radiation budget requires measurement of cloud base height, and radiative heating of the atmosphere is dependent on cloud vertical profile. Similarly, ice clouds are sources of upper tropospheric water vapor, which affects atmospheric heating.

Currently stated needs for cloud base and top heights to the nearest 30 m above ground level for at least five cloud layers cannot be met by existing space-based measurement systems or existing weather analysis and forecast models. Active remote sensing systems, both airborne and space-based, can help to meet these needs. For example, a radar on a high-altitude uninhabited air vehicle (UAV) operating at selected frequencies in the range of 20-100 GHz could provide surveillance of clouds over a theater of operations. Not only would such sensors provide nowcasting data, but also they would provide critical data for the forecasting models. Space-based active sensors are inherently limited in their sampling geometry, relative to passive sensors, by the need to illuminate each sampled volume. Nevertheless, intermittent measurements of cloud layers by a radar on a satellite could provide a "first guess" for retrieval algorithms used on passively sensed data or serve to verify the output of those algorithms.

Current trends in radar and related technologies indicate that such future applications are plausible. A variety of high-power sources for signals of 94 GHz and higher frequencies are now available. The use of these frequencies enables the achievement of small sample volumes with small antennas (a result of narrow diffraction-limited beamwidths). Newly developed transmitted waveforms and related signal processing techniques can yield higher spatial resolution, faster temporal sampling, and discrimination against unwanted signal components such as echoes from the ground and other clutter. Increased capacity of communication and computing systems permits the timely analysis of the measurements and dissemination of needed information.

Discussion to this point assumes a radar operating in a direct-backscatter mode. A particularly novel alternative to this approach is bistatic radar, where microwave sources of opportunity such as radars, radio and TV transmitters are used in the "non-cooperative" mode, and military transmitters, often remotely sited, are used in a "cooperative" mode. The usual advantages cited for such radars are covertness and self-protection, but for present purposes the principal advantage is in power and therefore weight, in that only the receiver need be carried aboard the airborne platform. Bistatic radars, operating at 5-10 GHz, have been shown to track major weather patterns, and to identify cloud locations and densities, as well as other aerosols that can affect sensor performance. At this time, bistatic radar is being pursued with vigor as a research activity, but as yet there is little emphasis on weather applications, except to remove the effects of atmospheric clutter as a source of unwanted signal.

Another novel approach using available rf sources is based on measuring GPS signals from a satellite-based receiver as the earth's atmosphere occults the GPS signals. The refraction of the signals is determined by temperature and moisture profiles that can in principle be retrieved. A great advantage of this concept is its putative low cost and global coverage.

Irrespective of the specific source of the data, there is a real need for additional development of algorithms for water content profile retrieval and prediction. Though the basic equations are understood, models suitable for predicting clouds and precipitation on a local scale are still far from satisfactory, partly because there have never been sufficient data to validate such models. A research program is therefore needed, ranging from the basic cloud physics to field measurements involving in-situ sensors and ground-based radars. One could then proceed to airborne or ultimately space-based radars. Particular emphasis needs to be placed in such developments on long grazing paths through the atmosphere, as it will not always be possible to have the sensor above the clouds of interest.

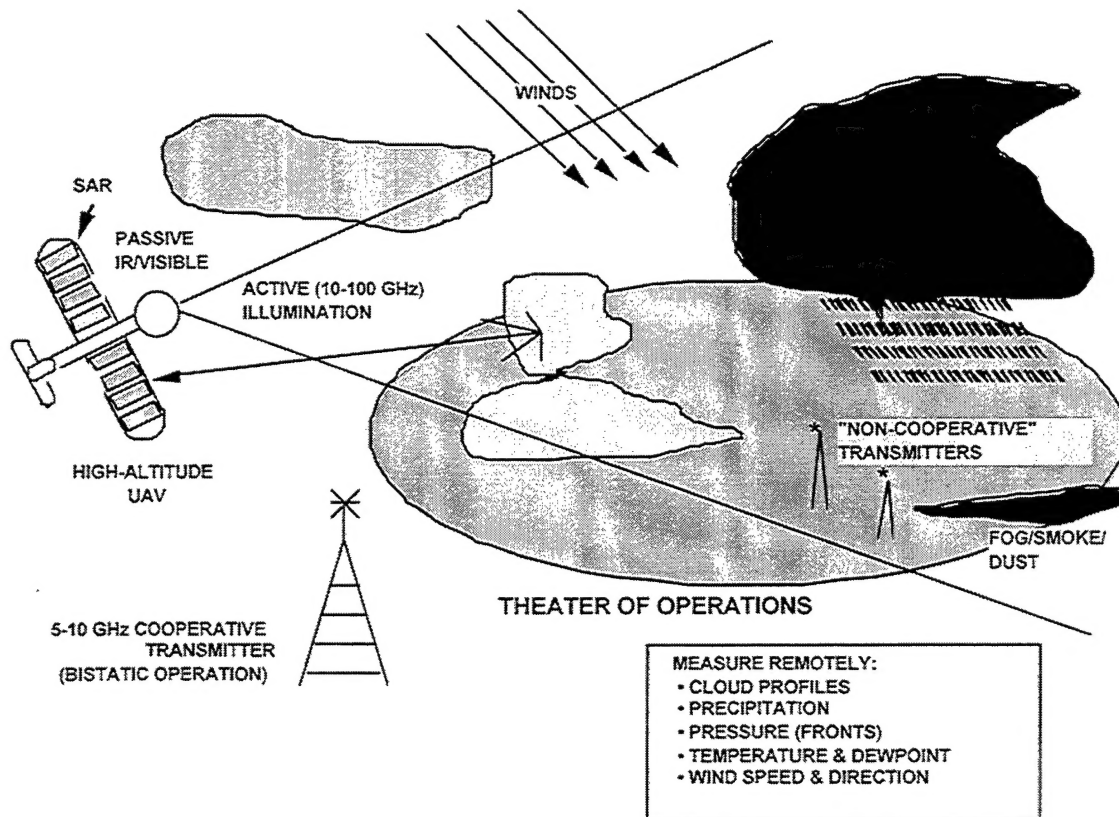
#### **4. ILLUSTRATIVE CONCEPT**

The biggest payoff in weather prediction for AF needs is clearly from the application of active sensors that can be dedicated to a specific region of interest. Emphasis needs to be put on determination of cloud conditions with a time frame of 0-12 hours. Though in principle this could be accomplished through the application of known technology to satellite platforms, the cost would be prohibitive, owing to the need for a number of satellites, or to considerable aperture and source power. This suggests that a few UAVs deployed in the general area of interest and observing with a collection of sensors could provide the relevant data. Though a suite of visible, infrared, and microwave passive sensors could be considered and would be of value, the emphasis would be on active microwave/mm-wave (that is, radar) sensors measuring cloud properties (densities, profiles, bases and tops, as well as detailing layers). These data would be fed into advanced models designed to predict weather (principally as related to clouds and precipitation) in theaters of operation. Unfortunately the algorithms are not sufficiently well developed to allow planning for how many such platforms would be required or how they would be employed. Unlike the requirements for tactical wide-area surveillance, the meteorological requirements are much more sparse. It is suggested that only a few such platforms (perhaps as few as one or two per 10,000 km<sup>2</sup>) would be sufficient. Obviously the number depends on local terrain (orographic features), and known weather patterns. Alternatively, if UAVs are developed for tactical wide-area surveillance, then weather data could be a byproduct.

A backup concept worth pursuing would have the UAV operating as a bistatic radar (that is, receive-only) at 5-10 GHz, and probably based on cooperative sources. This radar would have less utility in doing detailed forecasting, but could provide some useful data. How much utility is not known at the present time. The advantage of this would not be for covertness or protection of the asset (though this would be desirable), but would be to minimize on-board power required and therefore weight.

The illustrative concept is thus a high-altitude UAV (the higher the better) principally equipped with a radar operating in the 10-100 GHz region (probably 35 and/or 94 GHz), and secondarily equipped with a suite of passive sensors. The radar would concentrate on parameters associated with cloud formation and precipitation. An alternative approach would emphasize a lower frequency (5-10 GHz) bistatic radar. Advances in source and receiver technology are presumed, as well as significant advances in algorithms for local-area forecasting. Advantages of such a system would be better forecasting (as well as nowcasting) for efficient generation of the air-tasking order, to put personnel and equipment at least exposure and minimal risk in battle.

### GLOBAL WEATHER AWARENESS (ANYTIME-ANYWHERE)



## 5. TECHNOLOGY REQUIREMENTS

Many technologies need to be pursued to make global high precision weather-on-demand a reality. Commercial markets drive, and at the same time define, the limits of developments of many of these technologies, particularly in communication and computing. Limits in communication bandwidths effectively define the amount of data compression and on-board processing that must be employed. Straightforward image data compression techniques certainly apply to meteorological data, but these are seen to be insufficient. Specific algorithms and techniques are therefore needed for onboard processing of weather data.

In all cases, hardware miniaturization and affordability will be main drivers, in that many of today's sensors are already operating very near the physical limit of performance. Specific technologies where advances need to be pursued for improved performance, affordability, reliability, lifetime, and compactness, include (without regard for priority):

- Far-infrared sensors, cryo-coolers
- Alternative means of laser pumping
- Eyesafe solid-state lasers
- Lightweight telescopes
- Lidar detection techniques
- Doppler lidar
- Lidar temperature profiling techniques
- Synthetic-Aperture Radiometry
- High-power, high-frequency microwave sources (above 94 GHz)
- Phased-array antenna technology
- Space-deployable large-aperture antennas

The development of new retrieval algorithms and related data processing software are also required to assure that optimal meteorological information is extracted from the measurements.

The required radar technology will be driven more strongly by military requirements than by meteorology – including applications in reconnaissance, surveillance, and guidance systems – however, the needs of commercial air-traffic control will be significant as well. Laser developments will be largely driven by the commercial sector, as related to the field of fiber communications; however history has shown that the military labs have made remarkable improvements in laser performance through judicious investment of resources. What is needed are lasers, principally solid-state, with longer lifetimes, better reliability, and compact packaging. Sensors need advancements as well, in terms of larger array formats, and incorporation into interferometers. To support sensor performance, better, smaller, lower-cost, more-reliable cryocoolers are needed. To better refine techniques and technology, specific investments will be required in measurement programs, advanced algorithms for data interpretation, and techniques for using the data in weather analysis and forecast models.



## 6. CONCLUSIONS

Perhaps the field of global meteorological sensing can be characterized as one where the practitioners know what they want to do, but where they are limited by the state of the art. Invariably there is a time lag between being able to do something here on earth, and then doing it on orbit. Projecting 10-20 years into the future in this field is not so difficult, given that mostly what is required is more-compact, more-reliable, and longer-lived (that is, more affordable) systems. This is especially true for active sensors (lidars and radars) where the technology is well in hand on earth, but where the costs are literally prohibitive for placing the required capability in orbit.

Though we talk of the Air Force as having a global requirement, it is more correct to think of it as an "anytime-anywhere" need, given that the vast majority of projected Air Force missions will likely take place in narrow theaters of operation (for Operations Other Than War, such as humanitarian missions, peacekeeping, and intervention). This suggests a much stronger role in the near term for airborne sensors (including UAVs) that could cover only the specific theater, rather than the satellite that is expected to cover the globe. This would provide time for the technology developments that might ultimately lead to global weather awareness.